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Human Systems Program

DYNAMICS OF THE EYE AND HEAD WHEN SWITCHING VISUAL ATTENTION BETWEEN TWO TASKS

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Subjects were required, on command, to shift their attention from an ongoing manual control task to a peripheral monitor displaying digital information for a discrete processing task. Measurements were made of eye and head dynamics during the visual search and processing tasks. The independent variables of monitor angle, monitor discriminability, certainty of monitor location, processing task complexity and the subjects' tracking

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task performance status at the time of the visual search command were examined for possible effects on the visual search patterns. Dependent performance measures included the reaction times of the eye and head, the time to acquire the monitor and the pattern of saccadic eye movements during this period, the time of fixation on the monitor, the time required for the processing task, and the time to reacquire the control task.

In addition to quantifying these variables, the results present further evidence on the interference of a manual control task with refixation dynamics and new data supporting apparent visual processing of the monitor before its foveal fixation.

Introduction

Most research on the dynamics of vision during search has examined individual components of vision, isolated from the total search process. Since visual refixation is composed of a number of potentially interactive components, no single descriptive model has emerged. Some recent efforts, however, have attempted to examine the total visual process during movement from one information input to another.

Bartz (1966) examined the process of "seeing" a peripheral object and noted that the process involved identifying the location of the target, moving the eyes to it and interpreting the stimulus. Robinson, Koth and Ringenbach (1976) defined a total "element" of visual search as "the coordinated temporal sequence of eye and head movements beginning with the signal to refixate a new target and ending with a response to the discrimination of that target". Others (Bizzi, 1974; Noton and Stark, 1971; Robinson and Bond, 1975; Sanders, 1970) have similarly defined the visual process and have examined it while manipulating a variety of variables.

The visual process investigated in each of these studies can be broken down into (1) the initiation of eye and/or head movements towards a visual target, (2) the process of visually acquiring the target, (3) the process of fixating the target, and (4) the interpretation and response to the information presented at the target.

The temporal sequence of events begins with the reaction time of the eye, t_e, to a command to begin the search. A review of the literature shows that a relatively small range of t_e values, 190 msec to 230 msec, are found in experiments in which subjects were asked to change fixation between two points (Bartz, 1962; Becker and Fuchs, 1969; Diefendorf and Dodge, 1908).

Robinson and Bond (1975) found a considerably longer average t_e of 501 msec when subjects were asked to locate a peripherally undetectable target while performing an ongoing manual control task. Their results also indicated that when subjects were "out of control" on the tracking task their average t_e increased by 35 msec.

A number of other variables have been shown to affect t_e. Robinson, Koth and Ringenbach (1976) examined the eye's reaction time while varying both the discriminability of the target and the subject's knowledge of the target's location. Their results showed that average t_e values for the brighter, more discriminable targets were slightly longer than for the dimmer ones (214 msec and 198 msec respectively). The results also indicated that knowledge of a target's location prior to beginning the search decreased t_e by an average of 22 msec. Miller (1969) also varied the subject's knowledge of target location and found that knowledge of location decreased the average t_e for seven of his nine subjects.

The effect of target location on t_e is somewhat unclear. Bartz (1969) reported a non-linear increase in t_e with increases in display angle. His results indicated that t_e was relatively constant at display angles of ten degrees or less, but increased linearly at a rate of 1.5 msec per degree beyond ten degrees. Robinson and Bond (1975) also found that t_e increased as the target angle increased. Their results indicated a linear, two msec per degree rate of increase for display angles between 30 degrees and 120 degrees. They postulate this increase with angle to be entirely the result of the increased frequency of occurence of a period of eye/head compensation prior to t_e. This compensation pattern is apparently the result of their refixation task interrupting an ongoing manual control task. Robinson, Koth and Ringenbach (1976), however, in the more usual paradigm without an ongoing task found that t_e was not a function of display angle.

The second component of this visual sequence is the reaction time of the head to the command to begin the search, t_h, (if head movement occurs). Bartz (1966) and Sanders (1970) contend that head movements only occur when visually locating targets greater than 40 degrees from fixation. Vossius (1972), however, indicates that head movements occur when acquiring targets located at angles as small as ten or twenty degrees. Robinson, Koth and Ringenbach (1976) reported that head movements occured 78 percent of the time when locating targets at 40 degrees.

At least three different patterns of eye and head movement coordination have surfaced in the research literature. Originally it was believed that only one pattern of coordination existed. In this pattern the eye begins to move approximately 50 msec before the head (Bartz, 1966; Bizzi, 1974; Robinson, Koth and Ringenbach, 1976; Vossius, 1971).

In the second type of eye/head coordination the pattern is reversed, with the head moving before the eyes. Bizzi (1974) observed this in an experiment with monkeys. He found that when the monkeys were taught to predict the beginning of a search trial, they consistently moved their heads towards the target before their eyes. Robinson and Bond (1975) also observed this second type of coordination. They found that when a centrally located, manual control task was competing with a visual search task for the subject's attention, head movement preceded eye movement 63 percent of the time for targets at 90 degrees.

Sanders (1970) has reported a third pattern of eye/head movement coordination in which the eyes and head begin to move almost simultaneously.

At this point, the quantitative nature of these last two coordination patterns and when they might be expected to occur is relatively unknown.

The reaction time of the head has not been a frequently studied parameter of visual search. Robinson, Koth and Ringenbach

(1976) did observe t_h while manipulating both the subject's knowledge of target location, and the target's discriminability. Their results indicated that the average t_h for known target locations was 39 msec shorter than for unknown locations and that t_h for bright targets was 20 msec longer than for dim ones. They also reported a high correlation between t_h and t_e; on the order of 0.7 to 0.9 for individual subjects.

The next stage in the visual search process is the acquisition of the target. Gould and Schaffer (1965, 1967) found that decreasing target disciminability increased both the total number and duration of fixations. Robinson, Koth and Ringenbach (1976) observed the time required to acquire a target, t_a, and reported that it increased linearly with target angle between 40 and 80 degrees. Their results showed that at 80 degrees uncertainty in target location begins to affect t_a, increasing it by approximately 40 msec. They also reported that at 100 degrees t_a for dim targets was on the average 70 msec longer than for bright ones.

Becker and Fuchs (1969), studying only eye movements, found that most subjects when searching for targets located at an angle of 40 degrees required two saccades to fixate the target; a large amplitude saccade covering approximately 90 percent of the distance followed by a smaller corrective saccade resulting in foveal acquisition.

Bartz (1966) reported that when eye and head movements occur in visual search a single, large amplitude saccade and a single head movement combined to bring the direction of gaze to within a few degrees of the target. At this point the eye begins a backward, compensatory movement while the head continues to move towards the target. The final stage in this sequence is a small corrective saccade towards the target to foveally acquire it.

Robinson, Koth, and Ringenbach (1976) found the number of distinct eye movements (saccades and compensatory) to increase from approximately one with a 40 degree target to an average of three for a 100 degree target. They also report both location uncertainty and reduced brightness to increase this number by one or two movements for their larger target angles.

After the target has been located the subject processes the information presented there and gives the appropriate response. It is generally accepted that the processing stage begins after the target is fixated since visual processing is suppressed during saccadic movement (Matin, 1974).

Most of the experiments which have examined an element of visual search, as described above, have used stimulus identification for their processing task (Bartz, 1962; Neisser, 1964; Teichner and Krebs, 1974). Robinson, Koth and Ringenbach (1976) varied the information content of their target in an attempt to examine the effect of task difficulty on visual search dynamics.

Their results indicated that the programming and dynamics of visual search were independent of this dimension. To date this appears to have been the only experiment which has examined the possible interaction between an information processing task and the visual search process.

Another, potentially critical processing dimension is the explicit involvement of short-term memory during the programming and execution of the eye and head movements. Posner (1967, 1969) has proposed and experimentally demonstrated the relationship between processing time and reduction in information (bits) between possible input items and acceptable responses. His two tasks involved the addition of two sequentially presented digits (a reduction of three bits) and the reversal of the same digits (a reduction of zero bits). These two tasks are ideally suited for visual refixation experiments and will be used in the experiment to be presented here. The first digit was presented at the initial fixation point, and the second formed the peripheral target. The first must, therefore, be stored prior to the refixation dynamics and retained until the second is acquired.

The experiment to be presented here will utilize the same paradigm developed by Robinson and Bond (1975) with an ongoing, centrally located, manual control task which is randomly interrupted by a visual command to locate and process a digit presented at a target monitor in the subject's periphery. The

independent variables to be investigated are (1) the angular location of the monitor, (2) the discriminability of the digit presented at the monitor, (3) the level of uncertainty of the monitor's location, (4) the subject's control task performance at the time of command, and (5) the two processing tasks.

The dependent variables to be measured are (1) the total response time to locate a monitor and process the information, (2) the reaction time of both the eye and the head, (3) the number of distinct, saccadic eye movements before the monitor is fixated, (4) the time needed to visually locate the monitor and the search pattern during this period, (5) the fixation time at the monitor, and (6) the time for the reacquisition of the central control task.

Method

In this experiment a trial consists of the temporal sequence of events beginning with a command to refixate on a peripheral target and ending with the processing of that target's display. This paradigm thus follows the definition of a visual search element put forward by Robinson, Koth, and Ringenbach (1976). In addition, the observer is performing a manual control task at the time the command is received, and this task must be interrupted for the visual search. This paradigm was established by Robinson and Bond (1975).

The processing task is one of the two suggested by Posner (1967, 1969), with one digit presented as the command and the second as the target.

Design

A randomized block, factorial design (Kirk, 1968) was used with the subjects of the experiment being the blocking factor. Each block, or subject received all of the treatment combinations of the five independent variables.

The independent variables of the experiment were: (1) the angular location of the monitors (ten degree increments between 20 and 90 degrees in the right periphery), (2) two levels of monitor discriminability (60 and 150 percent contrast between the monitor and its background), (3) the subject's knowledge of the monitor's location at the beginning of a trial (either the subject is certain of the monitor's location, or there is

maximum uncertainty among the eight monitors), (4) the difficulty of the processing task (the reversal or the addition of two digits), and (4) the subjects tracking task performance status at the beginning of a trial (in or out of control).

The following dependent variables were measured during the experiment (see Figures 1, 2 and 3 for illustrations): (1) t_e, the reaction time of the eye to the command to begin the search, (2) t_h, the reaction time of the head to the same command, (3) t_a, the time required to visually locate the monitor, defined as the time at the end of the last saccade prior to monitor fixation, (4) the number of saccadic eye movements made prior to t_a, (5) $t_e^* - t_a$, the duration of the period of visual fixation at the monitor, (6) $t_a^* - t_e$, the time between the end of the monitor fixation period and the visual reacquisition of the tracking task display and (7) t_r, the subject's total response time for the processing task.

There were a total of six experimental sessions of 1 1/2 hours each. During each of the first four experimental sessions the subjects were given 80 trials, all at uncertain monitor locations, while during each of the final two sessions they were given 60 trials, all at certain monitor lcoations.

During the uncertain sessions each of the eight monitor angles (20 through 90 degrees) were used, while during the certain sessions only the 30, 60 and 90 degree monitors were

used. It was therefore necessary, in order to avoid uneven practice effects among locations, to complete all uncertain sessions first. In all sessions 40 trials were given to each subject at each monitor angle, five replications for each of the treatment combinations. Only data for the 30, 60, and 90 degree locations were analyzed for the uncertain trials.

Within each uncertain session monitor angle, monitor discriminability, control task performance status, and processing task difficulty were randomly presented. In certain location sessions the monitor angle was randomly changed only after every twentieth trial.

Training

A training session was given before the actual experiment began. This session began by familiarizing the subject with the apparatus and the manual control and processing task components of the experiments. The subject then performed the manual control task for 5 minutes. The subject then began a series of 1 1/2 minute manual control trials with performance (mean squared error) measured for the last minute of each trial. This training session continued until a reasonably asymptotic level of performance was reached. (This level was reached by all subjects within 40 trials.)

Subjects

Four male college students, 19 to 21 years of age with uncorrected 20/20 vision served as experimental subjects. Each subject was screened for compatability with the eye measuring instrument to insure valid measurements. Each was paid for his participation.

Apparatus

The peripheral monitors were horizontally arranged in a quarter circle of 90 cm radius with the subject seated in its center. The monitors consisted of digital RCA Numatron tubes, mounted approximately at eye level, and subtending a vertical visual angle of 1.02 degrees. The 0 degree monitor was located slightly below the tracking task display and served as a command to begin a search. It also presented a digit between one and nine for the processing task. The 0 degree monitor was constantly presented at 150 percent contrast (1.542 candelas/m^2 on a 6.16 candelas/m^2 background), while the peripheral monitors were presented at either 60 or 150 percent contrast (9.9 candelas/m^2 or 15.4 candelas/m^2 on a 6.16 candelas/m^2 background respectively). The lower level of contrast is slightly below the peripheral detection threshold at 20 degrees, while the higher level contrast is at the detection threshold at 90 degrees (see Appendix A).

The control task was presented on a 12 inch diagonal TV monitor linked via closed circuit TV to a dual channel oscilloscope. It used a pursuit display with a randomly moving dot as input (Gausian noise at .10 Hz with a maximum deflection of ± 3 cm, or 4 degrees) and a 1 cm diameter circle indicating the output of the controlled system. The operator controlled a second order system with a spring centered joystick, 17 cm in length, with a maximum angular deflection of ± 47 degrees corresponding to 1.0 cm/sec^2 controlled system output.

The total response time for a trial was measured with the use of a voice actuated timer.

Horizontal eye rotation, relative to the head, was measured with an infrared, corneal reflection type, eye monitor device (Biometrics SGHV-2). Although the experimental display was viewed binocularly, only the right eye's movements were measured. The monitor's error was less than two degrees for a 40 degree eye movement.

Head movement was measured using a potentiometer attached to the center of a bicycle helmet. The helmet was suspended from a counterbalanced, articulated arm, which allowed relatively free lateral movement for comfort while maintaining accurate angular reference.

An analog computer was used to generate the displays and simulate the controlled system.

Procedure

Response times for the processing tasks in the absence of any visual search were measured before and after each experimental session, for both bright and dim targets. These times were measured by sequentially presenting two digits at a monitor which was centrally fixated by the subjects. The digits were separated by a randomly chosen interval of from one to three seconds and the subjects were asked to either add or reverse the digits. Response times were measured from the onset of the second digit.

Each experimental session began by having the subjects perform the tracking task for five 1 1/2 minute periods. The eye movement measuring instrument was then calibrated and the experimental trials began.

Between three and six individual trials occured during a continuous 3 1/2 minute period of manual control. Both the exact number of trials and when they occured within the period were randomly determined. The subject's manual control performance was measured during the last three minutes of each period. The experimenter began an individual trial by simultaneously lighting the zero degree, command monitor and one of the peripheral monitors. The subject then left the manual control task, located the peripheral monitor, responsed by adding or reversing the digits (checked for error by the experimentor) and returned his attention to the manual control task.

During the 3 1/2 minute manual control period the experimentor created the out of control condition by inserting a step change of ± 1 1/2 cm in the input at random intervals. Approximately half of these steps were followed, after a random interval of from 1 to 3 seconds, by an experimental trial. It was unlikely that control was regained within this time interval.

At the end of the last experimental session the simple reaction time of the eye was measured for each subject. The subjects were instructed to fixate on the 0 degree monitor which was displaying the digit 1, and to move their eyes to the 20 degree monitor as rapidly as possible when the digit was extinguished. Reaction times were calculated from 20 replications.

Data Collection

All of the eye and head movement data was processed by an analog to digital converter linearized by a digital computer programmed with the eye and head calibration data, and then stored in digital form on magnetic tape. The data was then transformed by a Complot plotter into graphical form.

Results

Figures 1-3 show representative, individual trials of eye and head movement and resulting line of sight[1,2] for the three target angles and the four discriminability and location uncertainty conditions. The independent variables of control task status and processing task did not appear to affect these patterns. Also shown with each trial are the average number of saccadic eye movements and the average movement time ($t_a - t_e$) for that particular condition averaged over subjects, control task status, and processing tasks. These measures are also graphed in Figures 4 and 5 for comparison.

All three target angles show the progressive increase in complexity of movement from bright, certain through dim, certain; bright, uncertain; to dim, uncertain. The interaction between these three variables is clear.

The 30 degree target (Figure 1) showed little head movement until the dim, uncertain condition. For certain targets most trials consisted of one saccade. A second saccade appeared in a small number of bright, uncertain trials and two saccades

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1. All three angular measures are with respect to the center of the head rotation. The actual angle of the eye with respect to its own axis of rotation can be calculated from these graphs using the transformations derived in Appendix B.

2. Non-zero starting values may reflect the horizontal, manual control display position at the start of the trial.

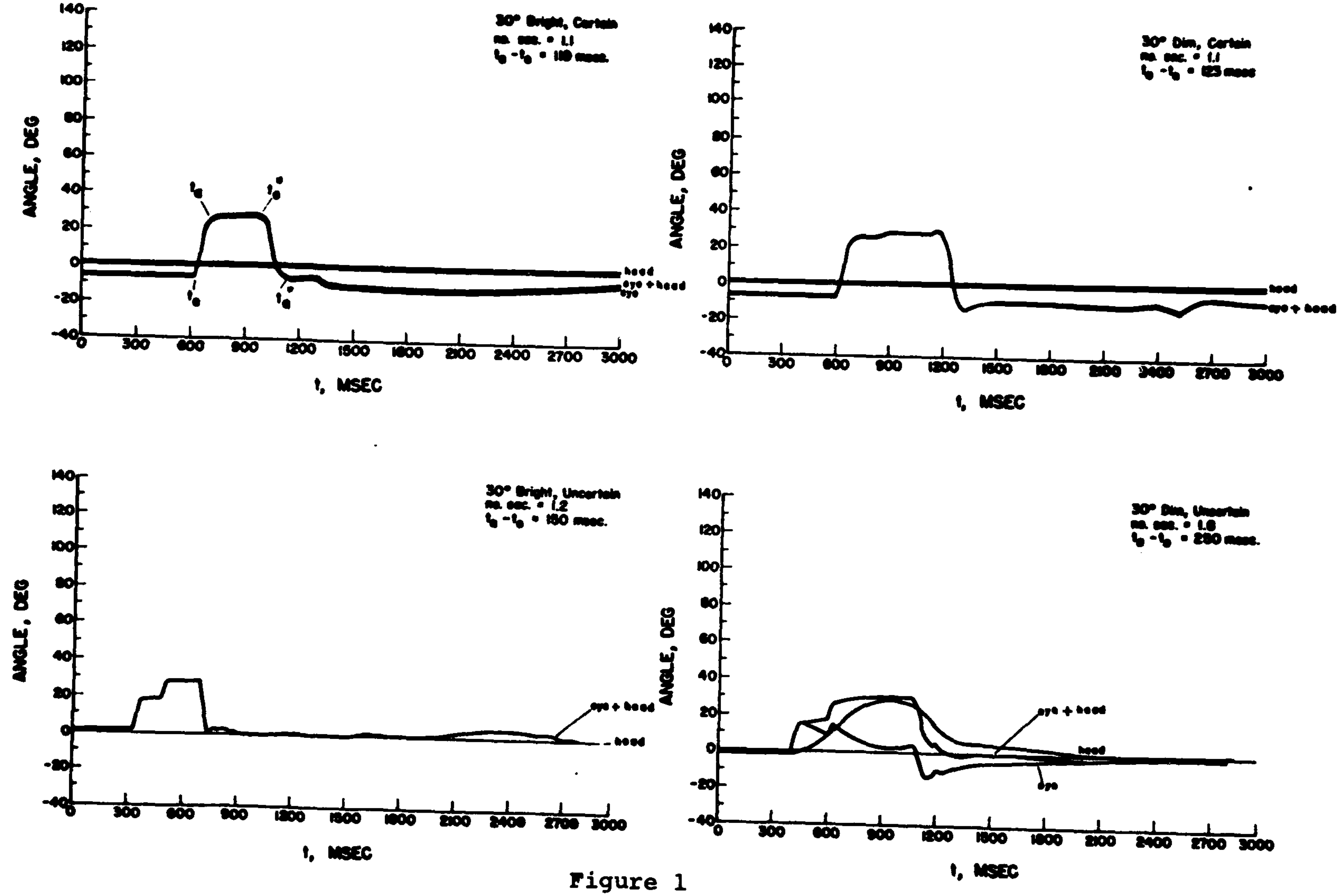

Figure 1

Eye Movement, Head Movement and Resulting Line-of-Sight. Target at 30 degrees under Four Conditions of Illumination and Certainty of Location. No. of Saccades and $t_a - t_e$ (msec) are average values over all trials and subjects. Data illustrated is from one, illustrative trial for one subject.

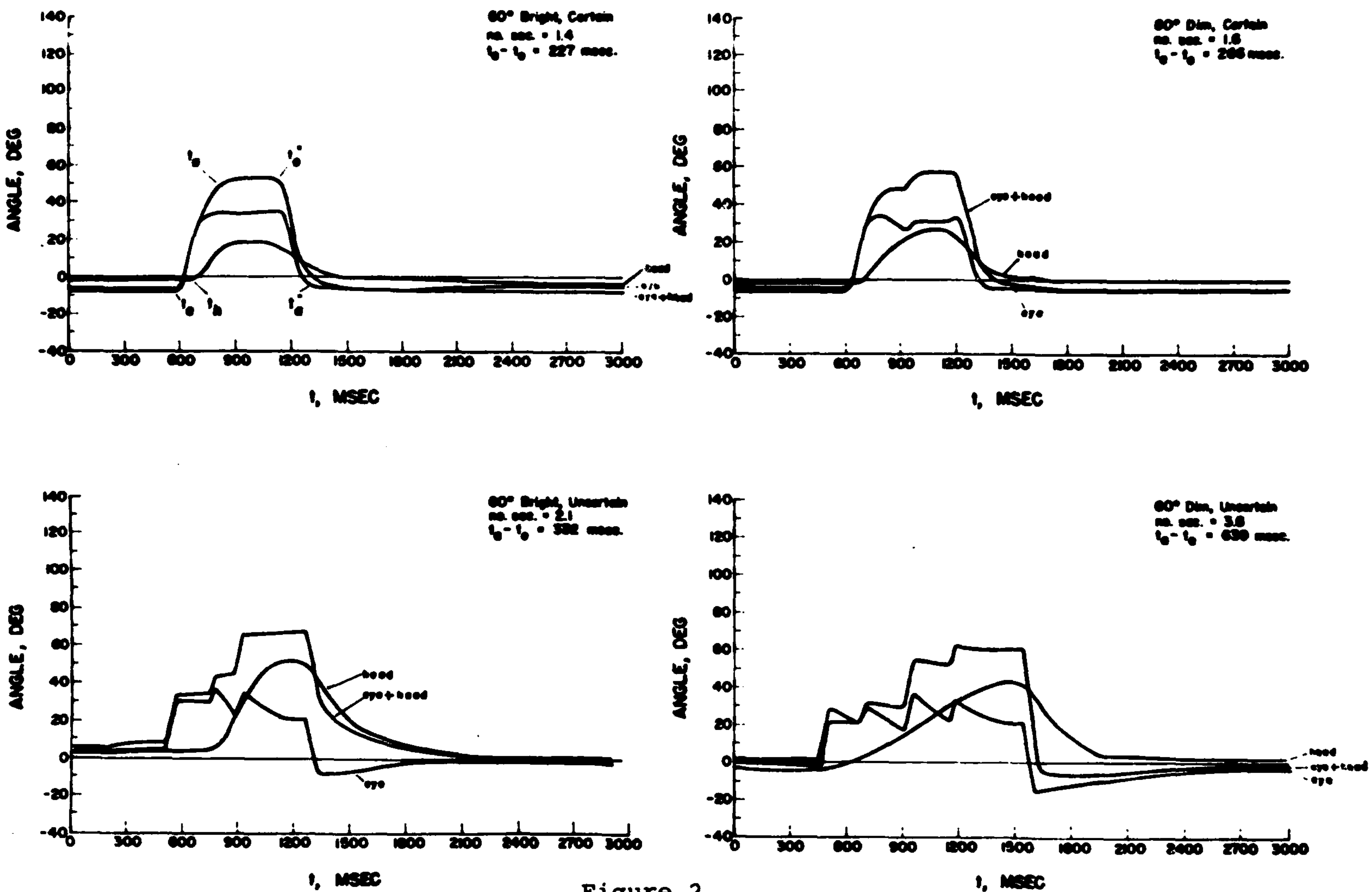

Figure 2

Eye Movement, Head Movement and Resulting Line-of-Sight. Target at 60 degrees under Four Conditions of Illumination and Certainty of Location. No. of Saccades and $t_a - t_e$ (Msec) are average values over all trials and subjects. Data illustrated is from one, illustrative trial for one subject.

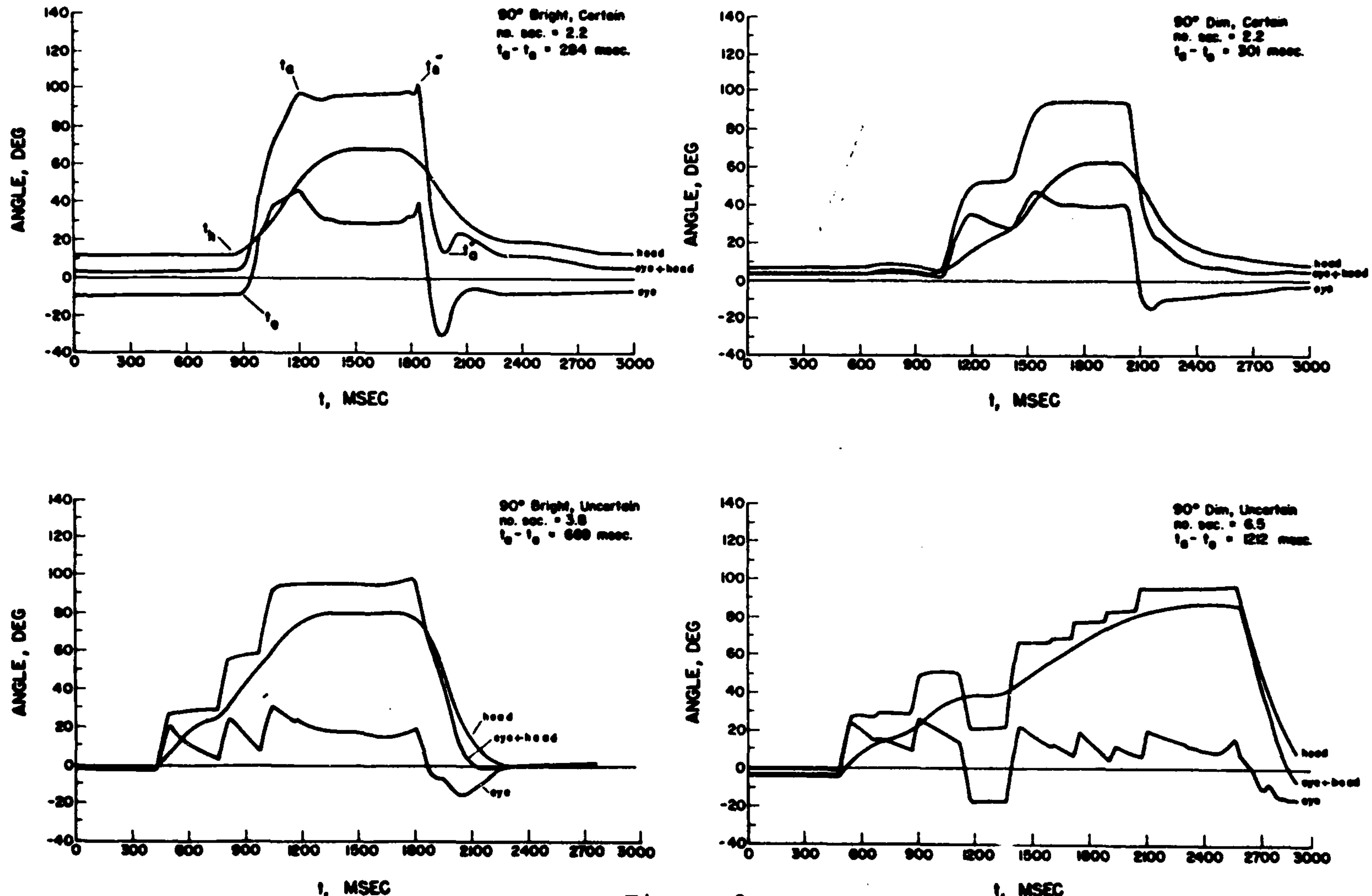

Figure 3

Eye Movement, Head Movement and Resulting Line-of-Sight. Target at 90 degrees under Four Conditions of Illumination and Certainty of Location. No. of Saccades and $t_a - t_e$ (msec) are average values over all trials and subjects. Data illustrated is from a illustrative trial for one subject.

appeared often in the dim, uncertain condition. The dim, uncertain trial in Figure 1 shows the first occurence of an eye/head compensation period before target acquisition, with the eye and head assuming equal and opposite velocities for a period of approximately 150 ms. This phenomina occurs frequently for the larger target angles; with seven pre-acquisition compensation periods shown for the 90 degree, dim, uncertain trial (Figure 3).

The 60 degree target (Figure 2) shows consistent head movement under all conditions. One or two saccades were required for the certain targets, with usually two for the bright, uncertain target and four for the dim, uncertain condition. The uncertain trials illustrate a number of the pre-acquisition, compensatory periods.

The 90 degree target (Figure 3) required from two to seven saccades, separated by compensatory periods apparently of similar form and duration observed to those for the 30 and 60 degree targets.

Return to the manual control display was usually accomplished with one saccade followed by a period of compensation.

Figures 4 and 5 show the average number of saccades and the average movement times ($t_a - t_e$) as a function of target angle and the four target conditions. Neither processing task nor control status affected these variables. All effects and interactions apparent in Figures 4 and 5 are statistically significant at $\underline{p} \leq .05$.

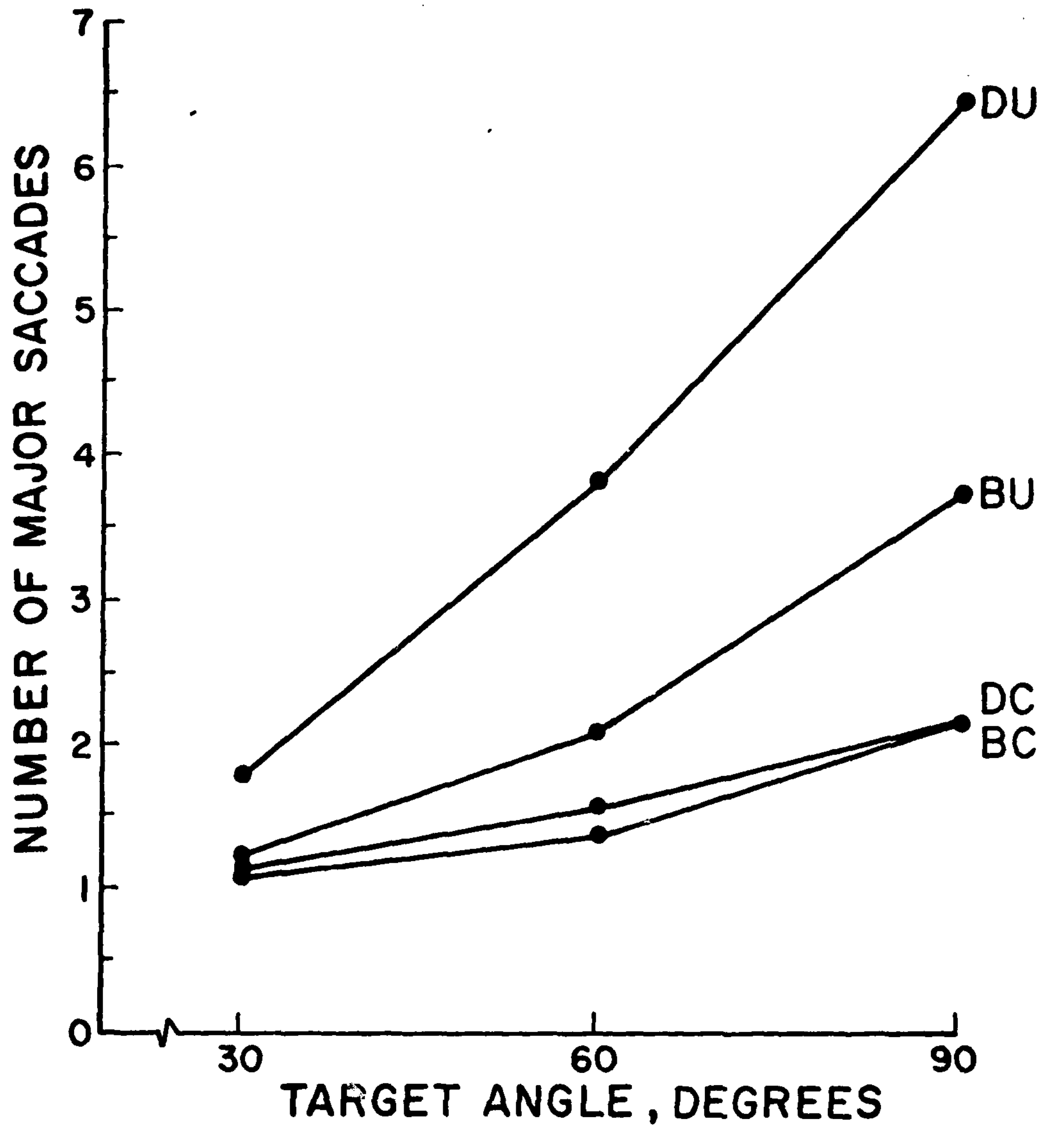

Figure 4

Average Number of Major Saccades as a Function of Target Angle for Four Conditions of Target Illumination and Certainty of Location

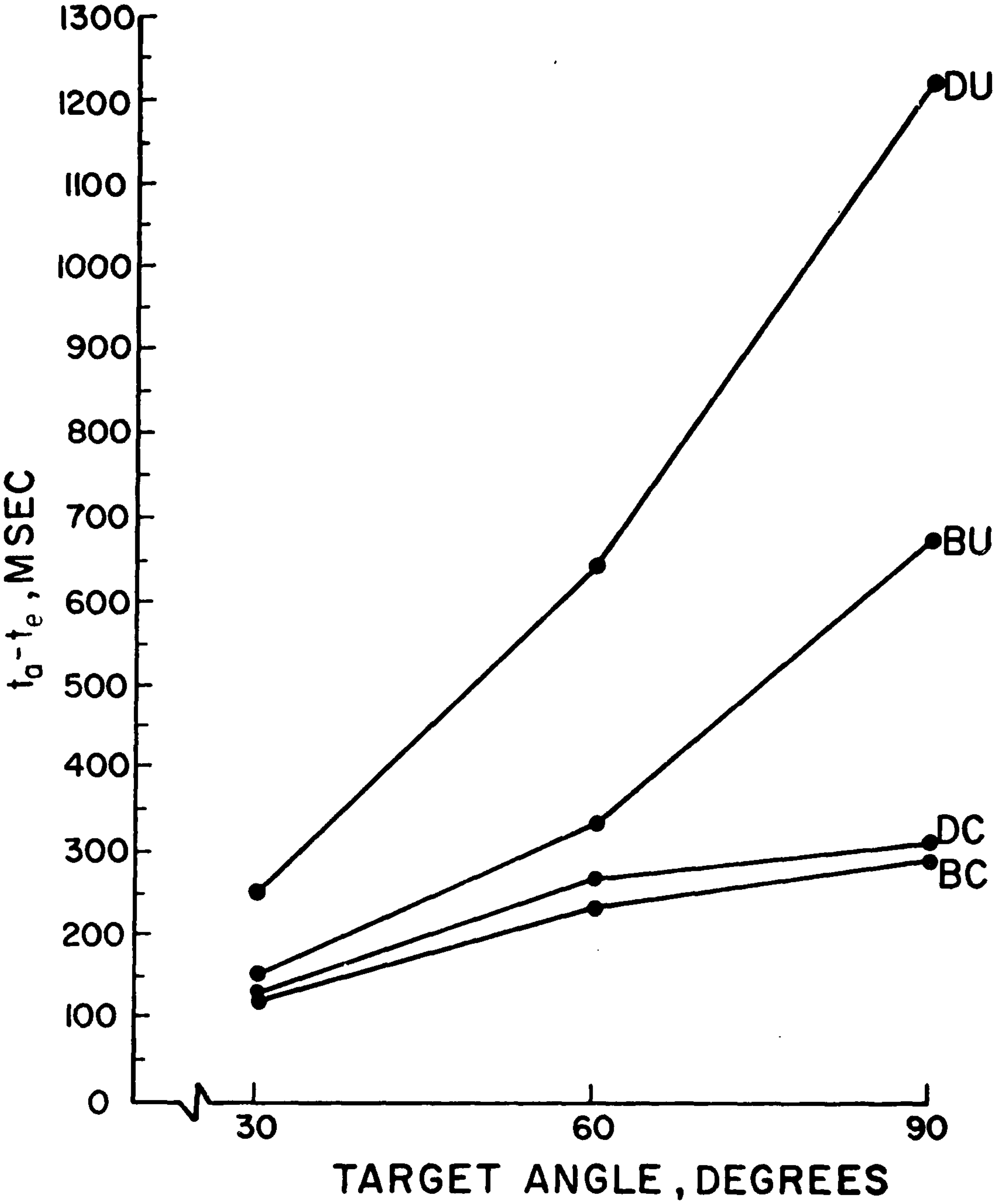

Figure 5

Average Time from Point of First Major Eye Saccade to Target Acquisition (t_a-t_e) (msec) as a Function of Target Angle for Four Conditions of Target Illumination and Certainty of Location.

Figure 6 shows reaction time of the eye (t_e) as a function of target angle and target location certainty. Eye reaction time (t_e) increases linearly with target angle for certain locations at approximately 2.2 ms/degree; while it is not a function of target angle for uncertain locations. This interaction is significant at $p < .05$. Eye reaction time was not a function of discriminability, control task status, or processing task.

The average value of t_e over all experimental conditions was 428 ms, compared to 204 ms for the same subjects without the manual control task.

Table 1 presents reaction time of the head (t_h) as a function of target discriminability and location uncertainty. The uncertainty difference is significant at $p < .01$ and the discriminability difference at $p < .05$. Their interaction is significant at $p < .05$. Head reaction time was not a function of target angle, control task status, or processing time.

At target angles of 30 degrees, head movement occured in 23 percent of the certain location trials and 65 percent of the uncertain location trials; difference significant at $p < .05$.

Time spent fixating the target ($t_e^* - t_a$) was a function of discriminability. Dim targets had an average value of 373 ms and bright targets 328 ms (difference significant at $p < .05$). Manual control status at the onset of the trial was also an effective variable, with out-of-control trials yielding values

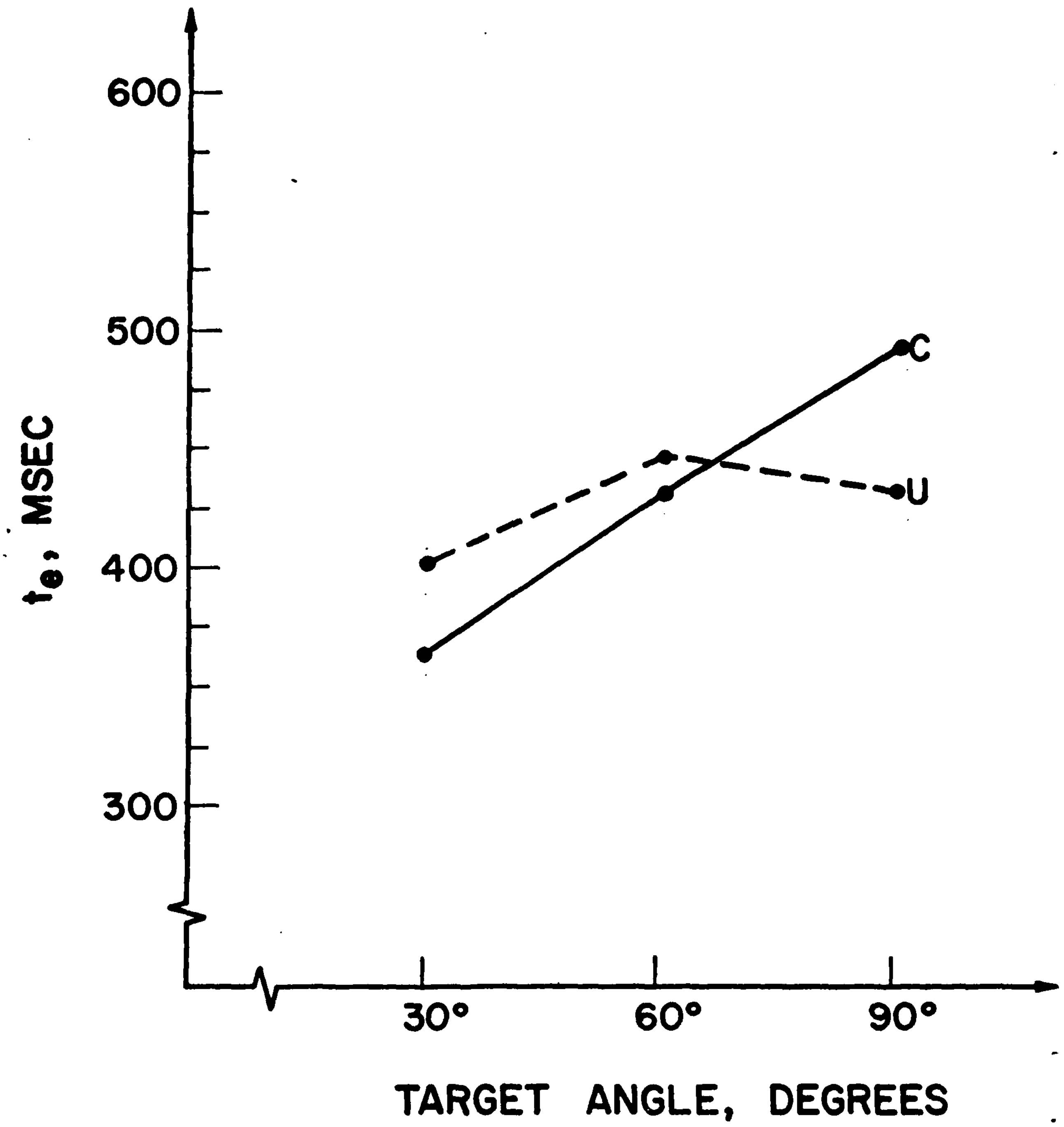

Figure 6

Reaction Time of the Eye (t_e; msec) as a Function of Target Angle for the Two Conditions of Certainty in Target Location; C = Certain, U = Uncertain.

Target Location Certainty	Target Discriminability		
	Bright	Dim	Means
Certain	470	478	474
Uncertain	532	556	544
Means	501	517	509

Table 1. Mean reaction time of the head, t_h, (msec) as a function of target discriminability and target location certainty.

of $t_e^* - t_a$ 21 ms less than in-control trials (significant at $p < .05$). Fixation time was not a function of location certainty, processing task, or target angle.

Table 2 shows processing time, defined as $t_p = t_r - t_a$, as a function of the processing task, target discriminability, and target location certainty. Table 2 also shows the reference processing times (t_p^*) measured without any required refixation (shown in brackets [ ]), and the difference between these two (shown in parentheses( )). This difference is the same variable identified and discussed by Robinson, Koth, and Ringenbach (1976) as "processing gain".

The systematic decrease in processing times without refixation (t_p^*) between the uncertain and certain conditions (120 ms, significant at $p < .01$) reveals subject learning between the first four sessions (uncertain) and the fifth and sixth sessions (certain). The "processing gain" values ($t_p - t_p^*$) are, therefore, calculated using the appropriate t_p^* values for the certainty condition, assuming that this processing skill acquisition occured also for the regular trials with refixation (t_p). Only the differences ($t_p - t_p^*$) should, therefore, be compared between the uncertain and certain trials.

The bright targets were processed with an average of 57 ms less time than the dim; consistant over all conditions and significant at $p < .01$. The reverse processing task was processed

Processing Tasks	Add		Reverse	
Discriminability	Dim	Bright	Dim	Bright
Location				
Uncertain	951[1170] (-219)	875[1043] (-168)	734[927] (-193)	695[847] (-152)
Certain	851[1033] (-182)	788[944] (-156)	665[813] (-148)	615[717] (-102)

Table 2. Processing Time ($t_p = t_r - t_a$)
Processing time without refixation (t_p^*) in brackets [ ]
Difference ($t_p - t_p^*$), in parentheses ( ). (msec)

in an average of 677 ms and the addition task 866 ms; the difference (189 ms) significant at $p < .01$.

Processing time was not a function of target location or control task status.

Processing task differences (processing gain; $t_p - t_p^*$) show an increase (in magnitude) from bright to dim targets (41 ms, significant at $p < .05$), and an increase (in magnitude) from reverse to addition processing task (32 ms, significant at $p < .05$).

Figure 7 shows the time required to reacquire the manual control task ($t_e^* - t_a^*$). This time was not a function of target discriminability, location certainty, processing task, or control status. Also shown in Figure 7 is the difference between this reacquisition time and the original, acquisition time for the bright, certain target $(t_a - t_e)_{BC}$, from Figure 5. Reacquisition was consistently faster, with the margin increasing with target angle.

Subjects was an effective variable on all measures, significant at $p < .05$.

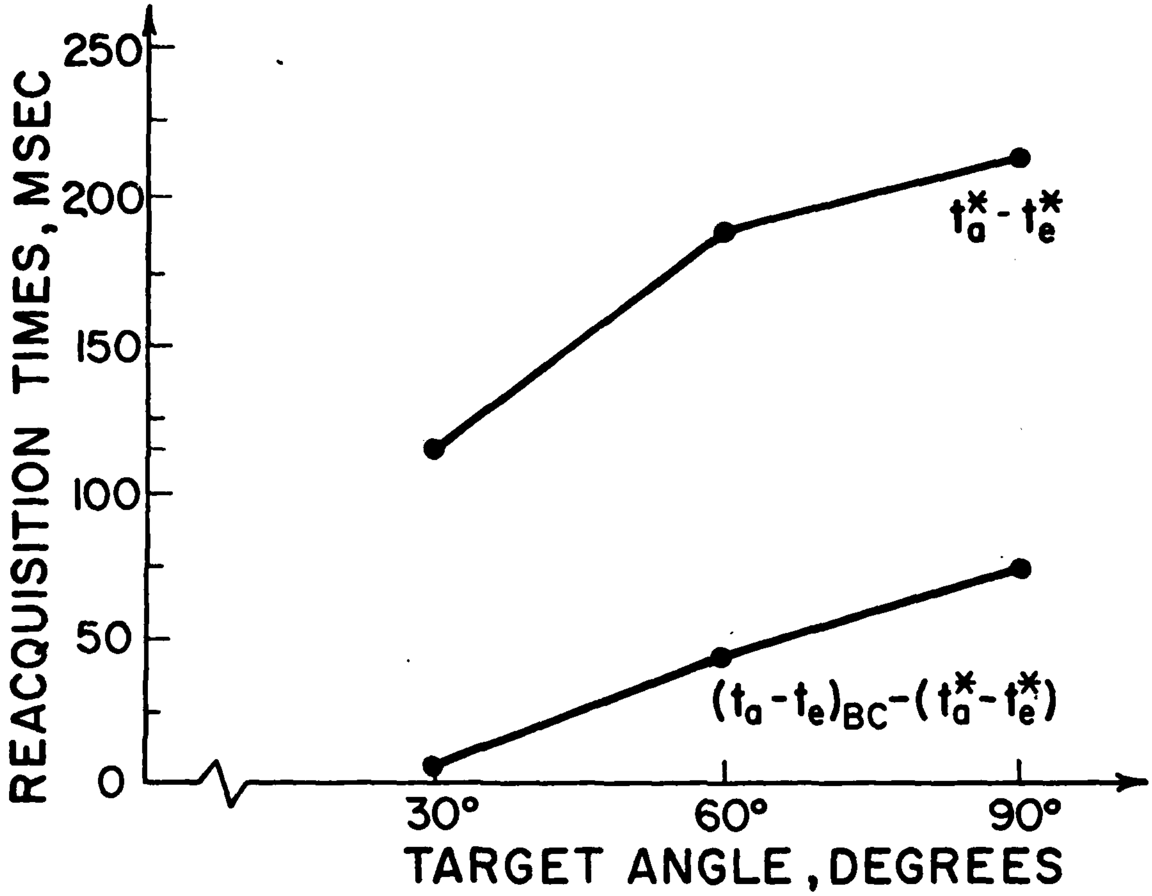

Figure 7

Time to Reacquire the Central Control Task Display ($t_a^* - t_e^*$) (msec) as a Function of Target Angle. Also; This time Subtracted from the Acquisition Time for a Bright, Certain Target (data BC, Figure 5)

Discussion

Reaction time of the eye, t_e

Reaction time of the eye, t_e, had a mean value of 428 msec. This can be most directly compared with that reported by Robinson and Bond (1975) who used a similar paradigm of interrupting a control task. Their mean value of t_e, over all experimental conditions, was 502 msec. Since their target locations were known, a more precise comparison can be made with the certain location data (Figure 6 "C"). The appropriate data from Robinson and Bond (1975) is the low bandwidth condition, which most closely approximates the control signal bandwidth used here. They found values of t_e of 453 and 620 msec for 30 degree and 90 degree target locations, respectively, compared to values of 364 and 493 msec for the corresponding angles here. The bandwidth of the manual control input was shown to be an effective variable in Robinson and Bond (1975) although the direction of the effect would predict an increased rather than decreased time for the even lower bandwidth used here. A confounding factor is the dynamically slower system used here.

The rate of increase of t_e with target angle for known target locations is in agreement with Robinson and Bond (1975) at 2.2 msec/degree compared to their 2.0 msec/degree. The lack of effect of target angle with uncertain location

(Figure 6 "U") may reflect less eye-head compensation prior to t_e, following the theory put forward by Robinson and Bond (1975) that increases in t_e with target angle are entirely due to the increased occurance of eye-head compensation.[1]

It ought to be noted that the subjects here had a reasonably normal t_e when not controlling; 204 msec compared with 199 msec in a similar paradigm without the control task used by Robinson, Koth and Ringenbach (1976).

The lack of effect of target discriminability does not replicate the finding of Robinson, Koth and Ringenbach (1976), although their effect was reasonably small (about eight percent between their bright and dim targets). The lack of effect of control task status at the time of refixation command does not replicate Robinson and Bond's (1975) finding of an increase with the out-of-control condition. Their increase was small, however; less than seven percent.

A further comparison can be made with Robinson and Bond (1975) in that they used a simple light for refixation command whereas here a digit both signalled the required refixation and had to be read into storage for the subsequent processing task. It seems clear that this additional task added nothing to t_e.

---

[1] Eye-head dynamics prior to t_e will be the subject of a subsequent report following a current study using an explicit payoff matrix between the control and search tasks. Data from the experiment presented here, the Robinson and Bond (1975) findings, and this payoff experiment will be brought together in this report.

Head Movement

Reaction time of the head, t_h, is significantly less for certain target locations (Table 1) which may again reflect the eye-head compensation prior to t_e for known targets. The value of 478 msec for the certain, dim target condition compares with Robinson and Bond's (1975) range of 437 to 543 msec depending on the actual percentages of trials having the compensation dynamic. The average delay of t_h after t_e for the uncertain targets (Table 1) is greater than 100 msec, suggesting both the probability that few of these trials had early eye-head compensation and that the head is often more delayed than has been previously reported. Robinson, Koth and Ringenbach (1976) report an average value of 50 msec delay, with a high correlation between t_e and t_h. It seems evident that this correlation is substantially reduced with the addition of the manual control task.

Head movement occured in only 23 percent of the 30 degree trials with certain location, compared to Robinson and Bond's (1975) 51 percent. They point out, however, a large variation in this measure over subjects (0 to 81 percent over four subjects). Of interest here is the additional finding that head movement increases significantly with uncertain location targets (from 23 to 65 percent). Both Bartz (1966) and Sanders (1970) report very little head movement below 40 degrees and they both used targets where location was well known in advance.

Dynamic Patterns of Eye and Head Movement

A number of qualitative and quantitative features of eye and head dynamics can be inferred from Figures 1-3. On the saccades themselves it can be noted that they frequently exceed 20 degrees, under all location and brightness conditions. This is in sharp contrast to Yarbus (1967) who states that under "natural conditions" saccades "usually" do not exceed 20 degrees. He quotes Lancaster (op. cit. P. 130) as stating that 99 percent of saccades are less than 15 degrees. This may actually not be a contradiction in that in most, reasonably static, vision situations refixations of large extent are not called for (eg reading) and there are often a large number of very small saccades during fixation on a stationary target.

On the form of the eye movements, very little overshoot was observed in our data, in agreement with Yarbus (1967) who found overshoot minimal for the larger saccades. This is in apparent contradiction to Bahill, Clark and Stark (1975) who find 70 percent dynamic overshoot but who also note this percentage decreasing with saccadic size. Weber and Daroff (1971) studied this phenomenon as a function of saccadic size and found overshoots rare for 30 degree saccades but occuring in nine percent of 10 degree saccades.

The pattern of saccades interspersed with periods of eye-head compensation is precisely like Vossius (1972) (Figure 9, case b) finding when the initial saccade did not reach the target, and presumably similar to Becker and Fuchs (1969)

"preprogrammed" package of two saccades, although they did not allow head movement. Weber and Daroff (1972) identify a period of about 125 msec used to form a corrective saccade which would be similar to our eye-head compensation periods.

These periods of eye-head compensation prior to target acquisition can quite reasonably be called periods of dynamic fixation, in that they are quite definitely allowing visual information to be acquired; at the least information on rejection of a non-target (see Figure 3, dim/uncertain for examples) and possibly information on the correct target (peripherally). This appears in possible contradiction to Bartz (1966) statement that "little information" is available prior to (static) fixation on the target itself.

The time required for target acquisition under certain location conditions (Figure 5) agrees both qualitatively and quantitatively with Sander's (1970) data. No comparitative data on uncertain locations were found. The number of saccades required for refixation (Figure 4) agrees in general with that reported by Robinson, Koth and Ringenbach (1976) although the effect of location certainly seems stronger in the present data. It is of interest to note the lack of effect of target brightness, even at 90 degrees, when the target location is known, *a priori*.

Target fixation ($t_e^* - t_a$)

Time spent fixating the single digit target averaged 350 msec compared to a value for a fixation during reading of 230

msec for college age subjects (Taylor, 1957) and a minimum value for reading an aircraft instrument of 340 msec (Fitts, Jones and Milton, 1950). Gould and Schaffer (1965) found an average fixation during search of a digital array of 310 msec.

The relatively small difference between the bright and dim targets (45 msec) reflects the fact that much of the time is used for programming and initiating the return eye and head movements. The small decrease in the out-of-control condition reflects the subject's attempt to further shorten this period but it may well be that it is already near its minimum value. The processing task may be causing some effect here, although no difference between these tasks was noted. There appears to be no evidence to date on the explicit involvement of short-term memory with the eye-head dynamic programming effort.

It is useful to note that neither target angle nor its location certainly had an effect on fixation time. This adds further weight to Robinson, Koth and Ringenbach's (1976) hypothesis that processing can be decoupled from search.

<u>Processing time</u> ($t_r - t_a$)

Processing time was longer for the addition task, in agreement with Posner's (1964) hypothesis. Of most interest here is a comparison of this time with its equivalent when no visual refixation is required. These values (shown in parentheses in Table 2) average -165 msec, the negative sign

indicating that processing must effectively begin before t_a, target acquisition. This is in general qualitative agreement with Robinson, Koth and Ringenbach (1976) but the differences are of the most interest. They found a strong effect of target angle, with little "processing gain" at the larger target angles, leading them to hypothesize processing before initial eye movement. No effect of target angle was found here, with the gain appearing at 90 degree targets under dim illumination, a condition in which processing prior to t_e is impossible. In fact, the findings here of increased gain with dim and uncertain location targets seems in contradiction to the Robinson, Koth and Ringenbach (1976) hypothesis. An interesting further complexity arises, however, with the inspection of the patterns in Figures 1-3. It can be noted that the dim, uncertain targets require fixations at near targets, particularly for the 60 and 90 degree locations. The possibility exists, therefore, that the Robinson, Koth and Ringenbach (1976) hypothesis is essentially correct but must be modified to include <u>all</u> periods of fixation prior to saccades and not simply the first, before any eye movement. A new experimental paradigm has been designed to further investigate this issue.

<u>Reacquisition of the control task</u>

Control task display reacquisition was qualitatively similar to original acquisition of a bright, certain target. The control task display was comparatively large, bright, and at a

well known location. It was actually acquired slightly faster than a bright, certain target; the difference increasing with the larger angles (Figure 7). Its relatively normal speed and lack of apparent interaction with the processing task appear to indicate no effect of parallel information processing with the actual execution of eye and head movements to known targets. The lack of effect of control task status appears to indicate that this response is already being accomplished in a minimum time and probably cannot be decreased by any appreciable degree.

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APPENDIX A

Estimation of Visual Detection Thresholds for Peripheral Displays

Peripheral visual stimuli can initiate a sequence of processes which result in the foveal acquisition of a target (Becker, 1972; Becker & Fuchs, 1969; Weber & Daroff, 1971, 1972). The sequence includes a main saccade designed to aim the fovea in the general area of the target and a number of smaller corrective eye movements which act to minimize the error between the orientation of the fovea and the target's location (Shebilske, 1974). Information about the spatial location of a target seems to "program" the first or main saccade. Becker (1972) has found that targets located up to $\pm$ 30° in the horizontal plane from cyclopean zero are capable of conveying enough information about their position to initiate the main saccade. These results indicate that the peripheral vision (at least up to 30° from the fovea) allows relatively sensitive position judgments.

This evidence appears to contradict peripheral acuity data, which indicates that acuity for stimuli located further than 20° from the fovea is less than ten percent of foveal acuity. The paradigm used in these studies usually investigates the eye's ability to detect a very dim light from a black background (brightness sensitivity). Since these studies do not examine the eye's ability to detect brightness differences between stimuli

(brightness discrimination), however, they cannot predict the complete detection behavior of the eye. It appears necessary to examine and quantify the peripheral brightness discriminability of the eye for a wide variety of stimuli and backgrounds. Such information should directly relate to the role of a stimulus and its background in initiating a sequence of saccades to acquire an object.

Wulfeck, et. al. (1958) reports contrast thresholds as a function of background luminance and object size for both rod and cone vision. The purpose of this paper is to determine these brightness discrimination thresholds for a specific digital display (RCA Numatron tube) for horizontal angular displacements from cyclopean zero of 20° through 90° at 10° increments. The resulting thresholds are used in the design of the principal experiment presented in this paper.

Method

Subjects

The subjects were two male and two female college students between 18 and 20 years in age. They had normal, uncorrected vision and were paid for their participation.

Design

A within-subject design was used in order to obtain brightness discrimination thresholds ($\Delta B/B$) estimates for each subject for all levels of the independent variables. The experiment's

two independent variables were the target brightness and the target angle from the fovea.

A range of target brightnesses, with a constant background luminance of 6.16 cd/m^2, was determined for each subject at each target angle location. This range was constructed between those brightnesses which were either missed or detected 100 percent of the time, and was then divided into 10 equal increments. These increments served as the levels of the independent variable of target brightness during the experiment.

The experiment consisted of five trials at each of the ten brightness levels, for each of the eight angles. Combinations of brightness level with target angle were randomly presented during the experimental session.

Apparatus and Procedure

The display lights consisted of RCA Numatron tubes capable of presenting digits from 0 to 9. The display's brightness could be varied by controlling their voltage. They were located 90 cm from the center of rotation of the subject's head and were approximately at eye level. The display numbers subtended a vertical visual angle of 1.02°. A fixation cross was attached to a monitor screen at cyclopean zero.

Each experimental session consisted of 20 practice trials and 400 (5 replications of each brightness x target location combination) experimental trials. A warning signal was given to indicate the beginning of each trial. The subject's task was to report whether they had detected the onset of one of the Numatron

displays within a three second interval following the warning signal. During each trial one of these displays was presented at one of the brightness levels prescribed for that angle. The subjects were not required to report the angular location of the Numatron tube.

The experimenter and subject were in different rooms and communicated via an intercom.

Since the subject's peripheral vision was being tested, it was necessary to monitor their eye and head position to insure that they fixated at 0° during each trial. An infrared corneal reflection eye monitor (Biometrics SGHV-2) was used to check eye position and a linear potentiometer attached to a bicycle helmet was used to indicate head position. The subjects were screened to insure that reliable eye and head position signals were obtained. None of this apparatus interfered with the subject's vision.

Results and Discussion

Brightness detection thresholds were computed for each subject at each target angle and are shown in Table 1. These thresholds were estimated by defining the first brightness level which was detected more than 50 percent of the time as the threshold.

Contrast thresholds for each target angle were computed across subjects and are shown in Figure 1.

The results are consistent with those of Wulfeck, et. al.

	Display Angle (deg.)							
Subject	20	30	40	50	60	70	80	90
#1	9.94	10.96	11.65	11.82	12.34	12.65	12.89	14.90
#2	9.59	10.59	11.45	11.84	12.40	12.64	12.86	14.80
#3	9.94	10.98	11.62	11.81	12.26	12.54	12.80	14.69
#4	9.94	11.20	11.72	11.79	12.34	12.65	12.88	14.74

Table 1--Detection thresholds for each display angle for each of the four subjects, given in cd/m^2 (constant background intensity of 6.17 cd/m^2 at each angle).

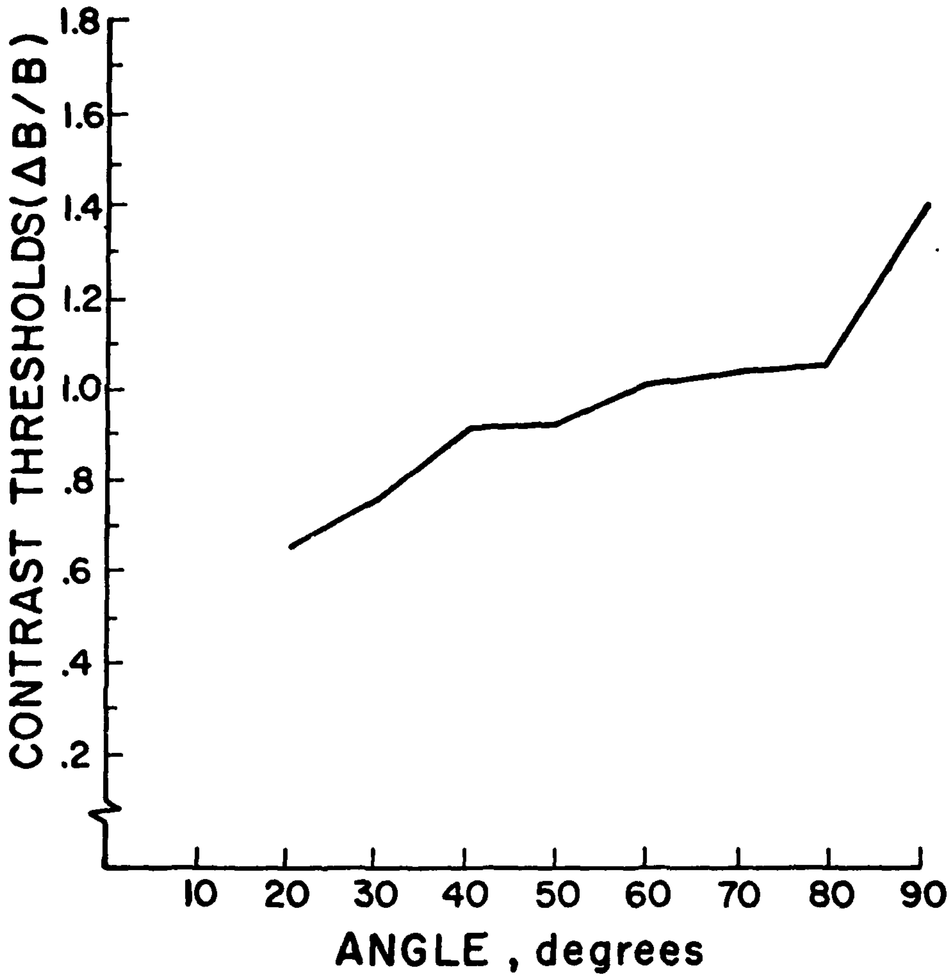

Figure A1

Contrast Thresholds ($^{\Delta B}/B$) as a Function of Target Angle. Averaged Across Subjects.

(1958), and indicate that the human eye is capable of detecting the presence of this stimuli with angular displacements up to 90°. The results thus allow the quantification of detectability of these stimuli.

APPENDIX B

Relation Between the Angle of Rotation of The Eye, Head, and Fixation

Jeffery R. Bond

Three primary measures involved in a study of visual dynamics are the angles of rotation of the eye, head, and resulting angle of fixation. These angles may be defined as: 1) the angle of rotation of the eye relative to the head (θ_e), 2) the angle of rotation of the head relative to a fixed reference frame external to the individual (θ_h), and 3) the angle of fixation (θ_f) measured relative to the same fixed reference frame as θ_h.

The common reference center for θ_h and θ_f is labelled the "system center" in this paper. This paper is limited to the horizontal components of these angles. Eye rotation is based on the measurement of one eye.

The purpose of this paper is to define the relationship between these three variables in order that one may be calculated from the other two. Since the rotational axis of the eye does not coincide with the system center, the relationship is not simply additive.

Anatomy

The relative displacement of the head and eye rotational axes may be broken into two components (Figure 1): the first (y) along the saggital (anterior-posterior) plane

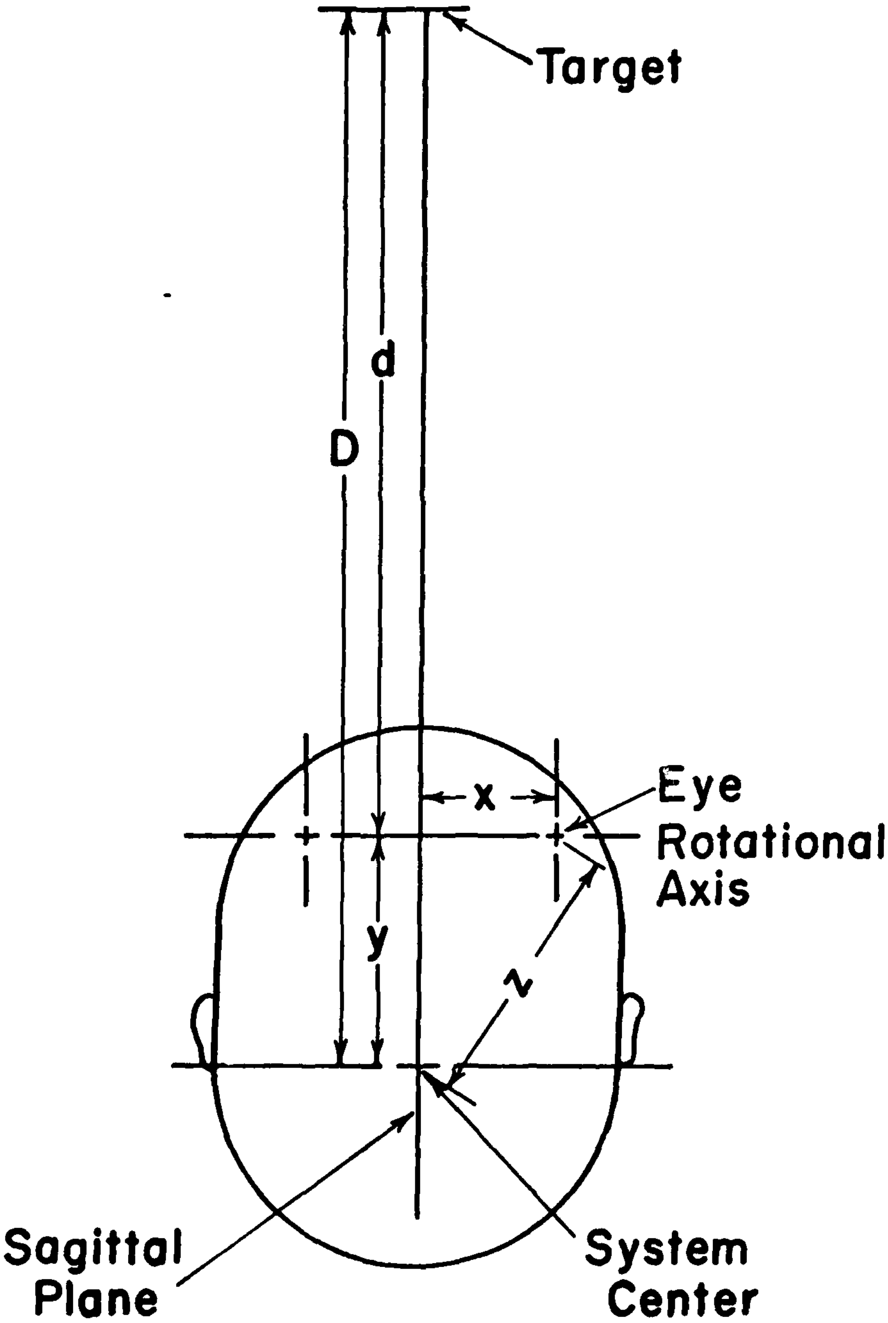

Figure B1- Dimensions

through the system center, and the second (x) through the eye rotational axis and perpendicular to the sagittal plane. It is also necessary to specify the distance (D) from the system center to the fixation point. The distance (d) is defined as (D - Y). As seen in Figure 2, the sum ($\theta_e + \theta_h$) is greater than θ_f by ($c_1 + c_2$).

<u>Equations</u>

<u>θ_h and θ_e given</u>

(c_1) is the angle due to the lateral displacement of the eye and system centers (Figure 2).

$$c_1 = \tan^{-1} x/d$$

(c_2) is the angle due to the sagittal displacement of the eye and system centers (Figure 2).

$$\sin c_2 = \frac{z \sin \varepsilon}{D}$$ (Rektorys, 1969, p. 119)

$$c_2 = \sin^{-1}\left[\frac{\sqrt{x^2+y^2}\ \sin \varepsilon}{D}\right]$$

$$\varepsilon = 360 - \alpha - \beta - \theta_e$$

$$= 360 - (\tan^{-1} y/x) - (\tan^{-1} d/x) - \theta_e$$

$$c_2 = \sin^{-1}\left\{\frac{\sqrt{x^2+y^2}\ \sin[360-(\tan^{-1} y/x)-(\tan^{-1} d/x)-\theta_e]}{D}\right\}$$

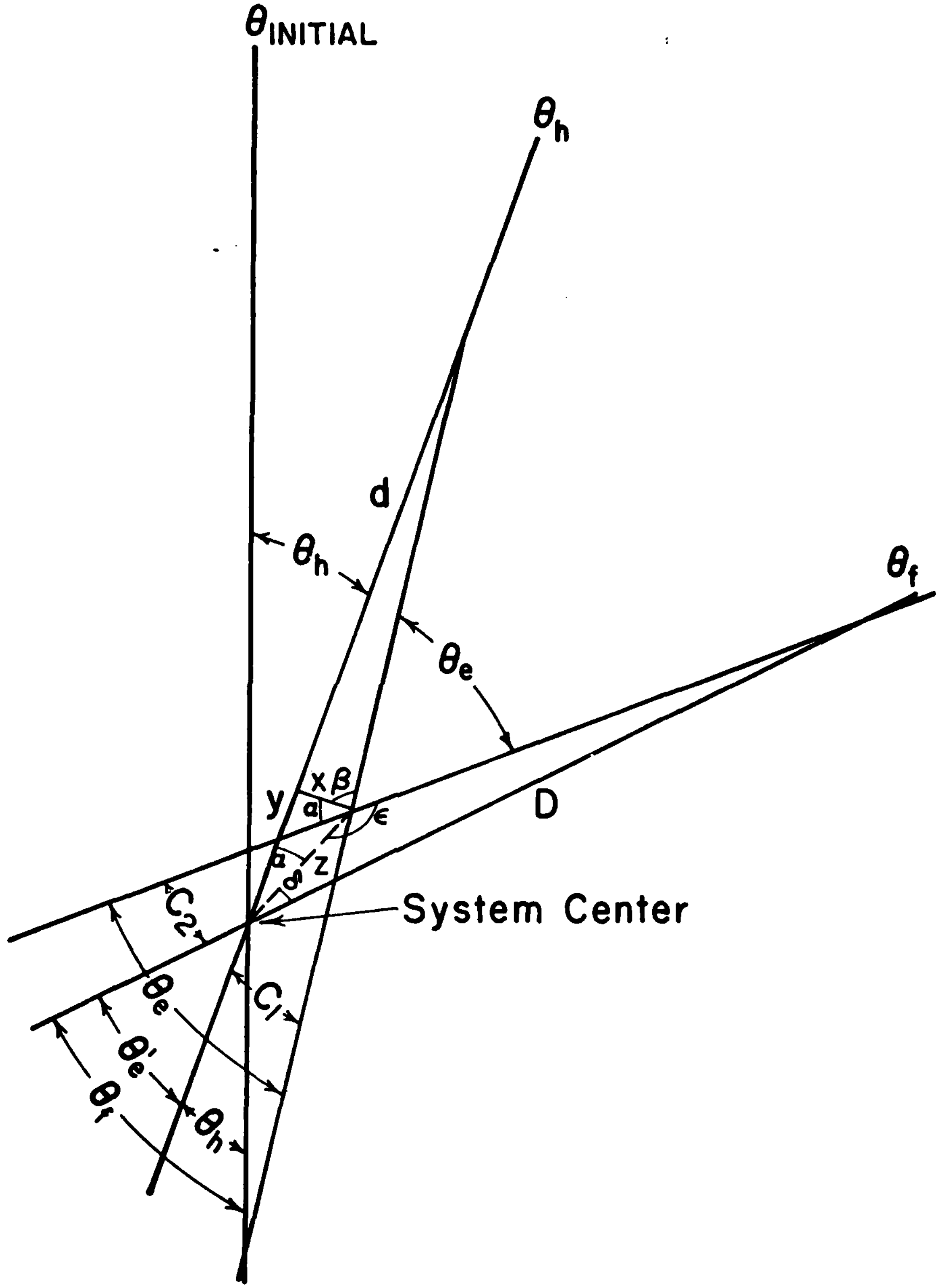

Figure B2 - Angles

Thus,

$$\theta_f = \theta_h + \theta_e - c_1 - c_2$$

$$= \theta_h + \theta_e - \tan^{-1}x/d$$

$$-\sin^{-1}\left\{\frac{\sqrt{x^2+y^2}\ \sin[360-(\tan^{-1}y/x)-(\tan^{-1}d/x)-\theta_e]}{D}\right\}$$

<u>θ_f and θ_h given</u>

$$c_1 = \tan^{-1} x/d$$

$$\tan c_2 = \frac{z \sin \delta}{D-z \cos \delta}$$ (Rektorys, 1969, p. 119)

$$c_2 = \tan^{-1} \frac{\sqrt{x^2+y^2} \sin \delta}{D - \sqrt{x^2+y^2} \cos \delta}$$

$$\delta = \theta_f - \theta_h - \gamma$$

$$c_2 = \tan^{-1} \frac{\sqrt{x^2+y^2}\ \sin[\theta_f-\theta_h-(\tan^{-1}x/y)]}{D - \sqrt{x^2+y^2}\ \cos\ [\theta_f-\theta_h-(\tan^{-1}x/y)]}$$

Thus,

$$\theta_e = \theta_f - \theta_h + c_1 + c_2$$

$$= \theta_f - \theta_h + \tan^{-1} x/d$$

$$+\tan^{-1} \frac{\sqrt{x^2+y^2}\ \sin[\theta_f-\theta_h-(\tan^{-1}x/y)]}{D - \sqrt{x^2+y^2}\ \cos[\theta_f-\theta_h-(\tan^{-1}x/y)]}$$

Numerical Solution

Distance

The distance (x) is the lateral displacement of the rotational axes.

$$x = 1/2 \text{ (interpupillary breadth)}$$
$$= 1/2\ (6.12)^{a}$$
$$= 3.06 \text{ cm}$$

The sagittal displacement is (y). (Figure 3).

$$y = \text{(occiput to external canthus)} - \text{(occiput to tragion)} + \text{(tragion to centrum of fourth cervical vertebra)}$$
$$= (17.19)^{b} - (10.46)^{c} + (2.22)^{e} = 8.95 \text{ cm}$$

If distance (D), from the system center to fixation point has been assumed to be 80 cm, then distance (d) is simply (D-y), 71.05 cm.

---

a. This distance was taken from a study of 4095 Navy recruits by Garrett & Kennedy, 1971:
   a. $\bar{x}$ = 6.12 cm, sd = 0.33 cm (p. 1134)

b,c: These distances were taken from a study of 4095 Navy recruits by Garrett & Kennedy, 1971:
   b. $\bar{x}$ = 17.19 cm, sd = 1.06 cm (p. 1421)
   c. $\bar{x}$ = 10.46 cm, sd = 1.34 cm (p. 1428)
   e. In previous literature, it has been assumed that the center of transverse head rotation is in the region of the centrum of the fourth cervical vertebra. Thus, distance e is utilized, as given in Devlin (1968) p. 6.

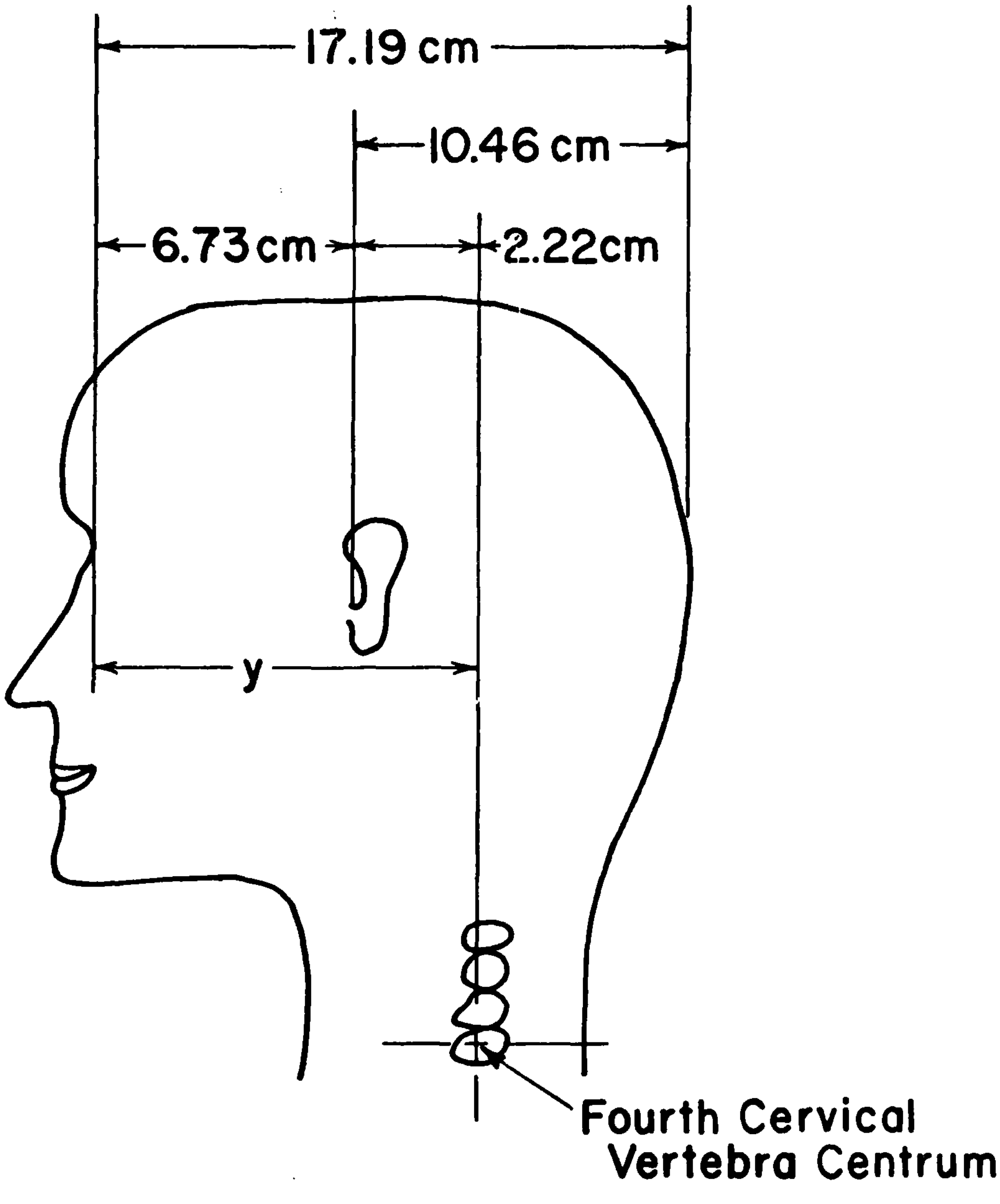

Figure B3 - Head Measurements

CASE A: θ_e and θ_h given

$$\theta_e = 40°$$

$$\theta_h = 50°$$

$$x = 3.06 \text{ cm}$$

$$y = 8.95 \text{ cm}$$

$$D = 80.00 \text{ cm}$$

$$d = 71.05 \text{ cm}$$

$$\theta_f = \theta_h + \theta_e - (\tan^{-1} x/d) - \sin^{-1}\left\{\frac{\sqrt{x^2+y^2}\ \sin[360-(\tan^{-1} y/x)-(\tan^{-1} d/x)-\theta_e]}{D}\right\}$$

$$= 85.37°$$

If θ_f was taken to be simply $(\theta_e + \theta_h)$, the percentage error would have been:

$$\left(\frac{90.00 - 85.38}{90.00}\right) \times 100\% = 5.133\%$$

c_1 is constant and c_2 varies as a function of θ_e (figure 4).

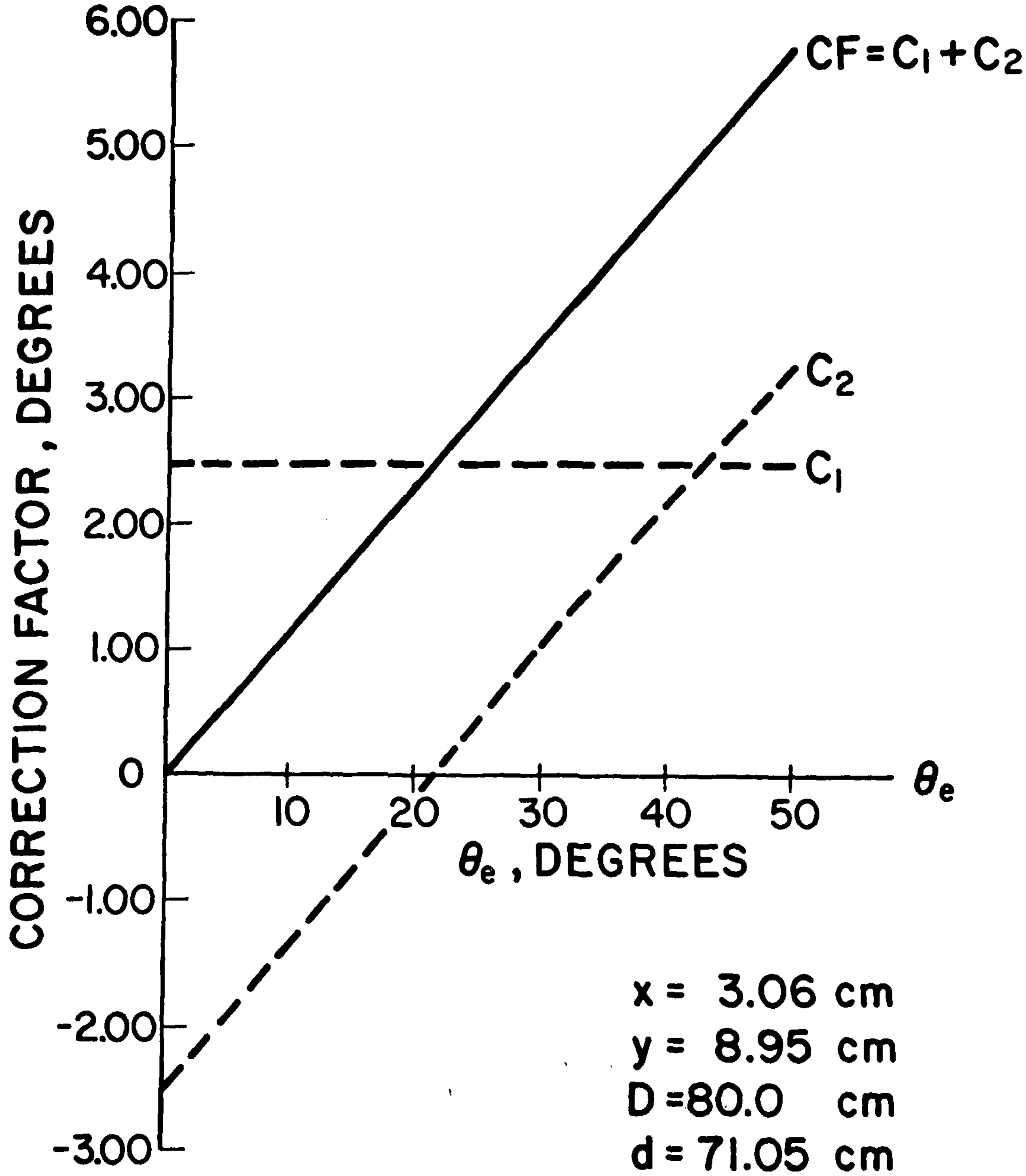

Figure B4

Correction Factor, Θ_e and Θ_h Given

CASE B: θ_f and θ_h given

$\theta_f = 90°$

$\theta_h = 50°$

$x = 3.06$ cm

$y = 8.59$ cm

$D = 80.00$ cm

$d = 71.05$ cm

$$\theta_e = (\theta_f - \theta_h) + (\tan^{-1} x/d) + \tan^{-1}\left\{\frac{\sqrt{x^2+y^2}\ \sin[(\theta_f-\theta_h)-(\tan^{-1} x/y)]}{D-\sqrt{x^2+y^2}\ \cos[\theta_f-\theta_h-(\tan^{-1} x/y)]}\right\}$$

$$= 44.21°$$

The percentage error, if θ_e had been assumed to be $(\theta_f - \theta_h)$, would have been:

$$\frac{44.21 - 40.00}{40.00} \times 100\% = 10.525\%$$

c_1 is constant and c_2 varies as a function of $\theta_f - \theta_h$ (Figure 5).

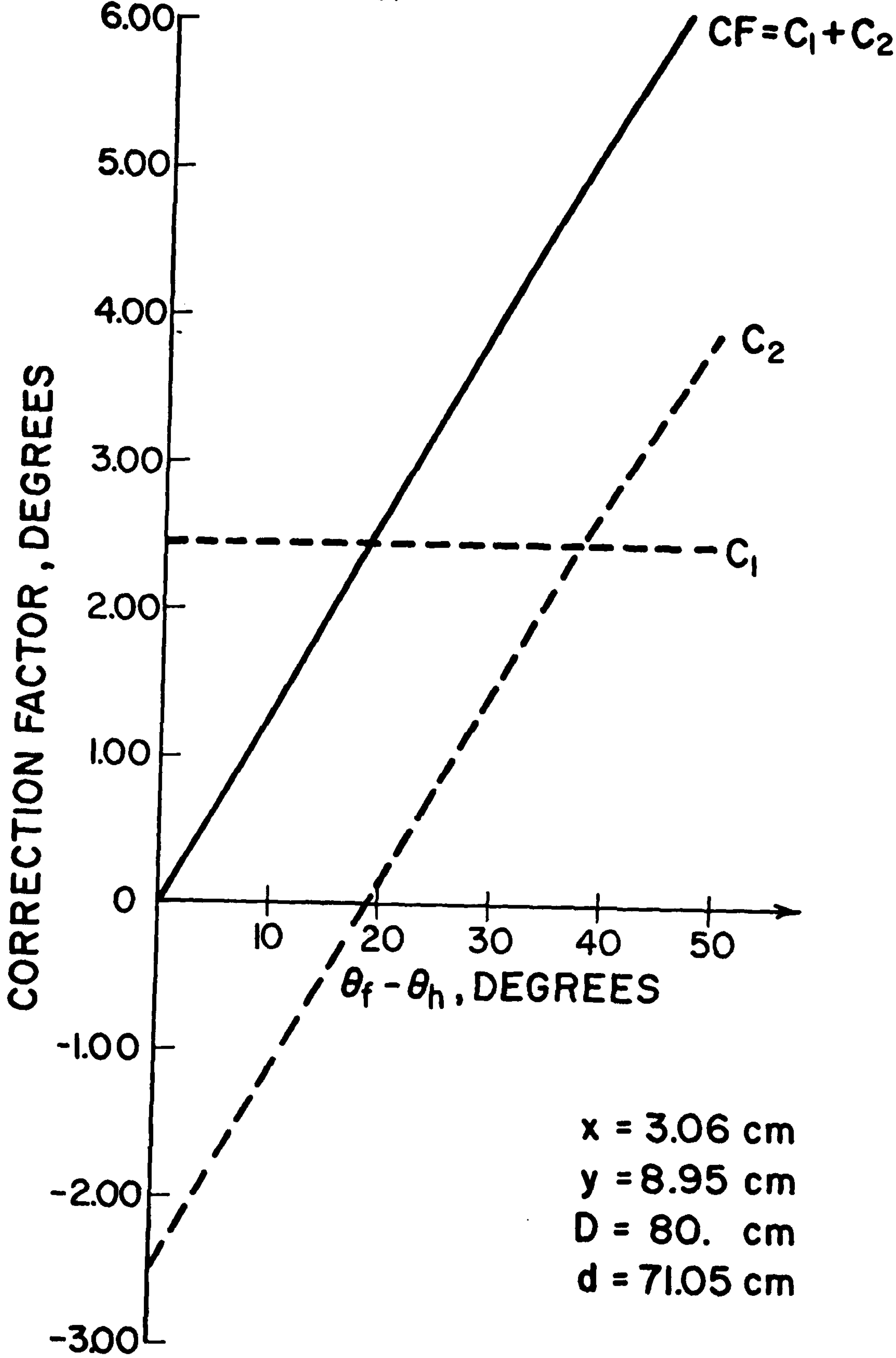

Figure B5

Correction Factor, θ_f and θ_h Given

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